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## FEATURES OF THE DISTRIBUTION NON-METALLIC INCLUSIONS IN THE STRUCTURAL ZONES OF A 24.2 TON INGOT OF 38XH3MΦA STEEL

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## ABSTRACT

The paper reports findings on the distribution of non-metallic inclusions in the structural zones as well as throughout the mass of a 24.2 ton ingot of 38XH3MΦA steel. It is shown that the distribution of non-metallic inclusions in steel varies throughout the height and cross-section of the ingot. The amount of sulfide and oxysulfide inclusions exceeds that of oxides. It is discovered that the inclusions are presented by compound oxides of manganese, silicon, vanadium, chromium and aluminum; besides, there are sulfide and oxysulfide inclusions as well.

The findings prove that there exists a correlation between the contamination index of sulfides and oxysulfides on the one hand, and the ingot height, on the other hand. In the upper part of the ingot, below its hot top, the distribution of the inclusions and their numbers almost fully coincide due to extended heat exposure. In the middle and bottom parts of the ingot in the zone of columnar and large randomly oriented crystals there is a pronounced inverse relation between the distribution of sulfides and oxysulfides.

The investigation of inclusions reveals the major role of oxysulfides in the formation of sulfides which are generally located at grain boundaries and reduce metal ductility. This is particularly important for vacuum cast steel since oxygen shortage reduces the amount of oxysulfides and leads to the escape of sulfides and an undesired form.

## Key words:

non-metallic inclusions, strength and ductile properties, large ingots, solidification, oxides, sulfides, oxysulfides

## 1. Introduction

The production of large forgings with a homogeneous chemical composition to manufacture power engineering components is a challenging task because it is required to ensure uniform properties evenly distributed throughout the mass of large-size

parts of high capacity units.

The formation of non-metallic impurities is closely related to melt solidification, and these relations affect the formation of grain size and its structure. As a result, a plastic and elastic deformation field is formed, and this field determines the properties and machinability of the part to be manufactured.

Table 1. Ladle sample chemical composition of steel 38XH3MΦA									
Chemical composition, %									
C	Mn	Si	S	P	Cr	Ni	Mo	V	
0.39	0.39	0.30	0.012	0.014	1.30	3.13	0.40	0.12	

The mechanical properties of steel products are primarily affected by sulfur. It is conditioned by the fact that the sulfide phase, which escapes from metal, distorts metal matrix homogeneity [1, 2]. The degree of sulfur negative impact depends, first of all, upon the type and shape of non-metallic inclusions containing sulfur. It is a well-established fact that such inclusions can be present in the form of both sulfides and oxysulfides depending upon the physical and chemical properties of the melt when such inclusions are being formed.

The formation of oxide, sulfide and oxysulfide inclusions is closely interrelated; the elastic parameters of a finished product can considerably vary throughout the mass of the piece, depending upon the amount of such inclusions. As a result, the study of the morphology and distribution of inclusions throughout the ingot mass is an important task because it may facilitate the control of sulfide and oxysulfide formation in order to ensure the reliability of heavy duty products throughout their service life.

## 2. Experimental methods

The study was performed on 24.2 ton ingot of vacuum cast 38XH3MΦA steel, steel chemical composition is given in table 1. Test specimens were cut out from the ingot in the transverse direction at six levels (fig. 1).

The identification of non-metallic inclusions was performed using a metallographic method [3]. The evaluation of steel contamination with nonmetallic inclusions was made with the NEOFOT 7 microscope on non-etched specimens as per the method L (GOST 1778-70).

The following parameters were assessed: total number of inclusions, loose inclusions, their shape, colour, mutual arrangement (in groups, in chains, singularly). Specimen contamination was evaluated separately for oxide, sulfide and oxysulfide inclusions at the outer edge of the ingot, in its middle part and within the centerline area. The maximum error for contamination assessment is  $0,75 \cdot 10^{-3}$ .

## 3. Results and discussion

Based on the results of the study performed, the following types of compound oxide inclusions were identified:  $\text{FeO} \cdot \text{MnO}$ ;  $2\text{FeO} \cdot \text{SiO}_2$ ;  $2\text{MnO} \cdot \text{SiO}_2$ ;  $\text{MnO} \cdot \text{SiO}_2$ ;  $n\text{FeO} \cdot m\text{MnO} \cdot p\text{SiO}_2$ ;  $\text{FeO} \cdot \text{V}_2\text{O}_3$ ;  $\text{FeO} \cdot \text{Cr}_2\text{O}_3$ ;  $(\text{FeO} \cdot \text{MnO})_2 \cdot \text{Cr}_2\text{O}_3$ ;  $\text{FeO} \cdot \text{Al}_2\text{O}_3$ . The  $\text{FeO} \cdot \text{MnO}$  solid solution of iron and manganese accounts for the greater portion of the above inclusion types and is equal to 26% of the total amount of all inclusions.

This compound oxide is rich in (FeO) which is conditioned by a relatively low manganese content in this grade of steel (not greater than 0.55%) [4]. The oxide inclusions are randomly located, groups of 3–5 inclusions sometimes occur.

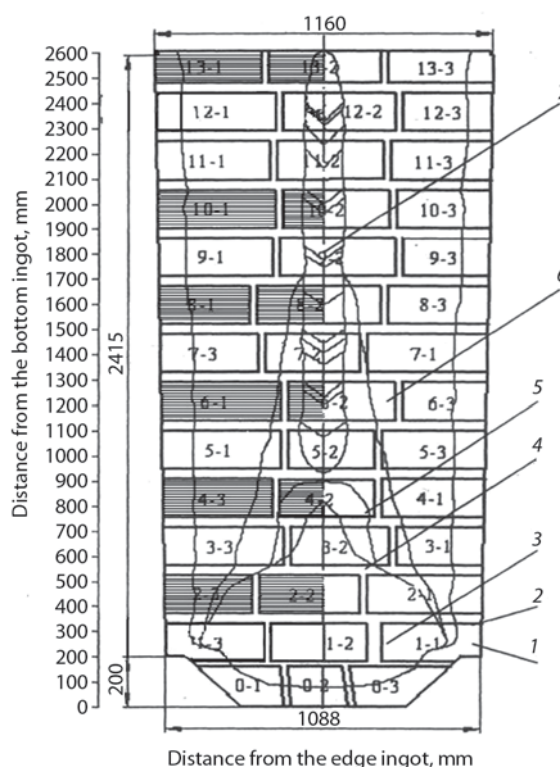


Fig. 1. Schematic diagram of cutting out test specimens to determine contamination index:

- 1 — crust zone; 2 — columnar crystal zone;
- 3 — bottom cone; 4 — zone of arc-shaped cracks;
- 5 — zone of fine randomly-oriented crystals;
- 6 — zone of large randomly-oriented crystals;
- 7 — axial sponginess zone

Inclusion features and the chemical composition of steel indicate that there occur glassy spherical silicate inclusions. Fayalite (iron silicate inclusions) ( $2\text{FeO} \cdot \text{SiO}_2$ ) amounts to 20%.

The second most frequently observed type of oxide inclusions in the ingot are manganese silicates: tephroite ( $2\text{MnO} \cdot \text{SiO}_2$ ) and rhodanite ( $\text{MnO} \cdot \text{SiO}_2$ ) which amount to 21% and 15% respectively. The inclusions are of globular shape and are randomly located.

Compound silicates of iron and manganese ( $n\text{FeO} \cdot m\text{MnO} \cdot p\text{SiO}_2$ ) occur in the ingot, they amount to 10%. The inclusions are randomly located. Vanadites ( $\text{FeO} \cdot \text{V}_2\text{O}_3$ ) were also identified in the amount of about 1.5%.

Supposedly, based on the ingot chemical composition, there may be present small quantities (3%) of chromium oxides ( $\text{Cr}_2\text{O}_3$ ).

Alongside with chromites, compound chromite inclusions, embedded in the  $\text{FeO} \cdot \text{MnO}$  solid solution, were identified; they amount to approximately 3%.

The ingot also contained  $\text{FeO} \cdot \text{Al}_2\text{O}_3$  aluminates, amounting to 0.5%. The number of oxide inclusions in the ingot is given in tab. 2.

The sulfide phase in the ingot is presented by a solid solution of sulfide iron and manganese. The sulfides are randomly located, their shape resembling that of type 1 and 3 sulfides according to K. S. Sim and F.B. Dal's classification.

Oxide type	Oxide content, % vol.
FeO×MnO	26
2FeO×SiO <sub>2</sub>	20
2MnO×SiO <sub>2</sub>	21
MnO×SiO <sub>2</sub>	15
<i>n</i> FeO× <i>m</i> MnO× <i>p</i> SiO <sub>2</sub>	10
Cr <sub>2</sub> O <sub>3</sub>	3
Cr <sub>2</sub> O <sub>3</sub> ×FeO×MnO	3
FeO×Al <sub>2</sub> O <sub>3</sub>	0.5
FeO·V <sub>2</sub> O <sub>3</sub>	1.5

The oxysulfide phase in the ingot is presented by compound manganese sulfides, containing the oxides (FeO, MnO, SiO<sub>2</sub>) and FeS. The oxysulfide inclusions are of globular shape, unevenly distributed, chains occasionally occur. These inclusions are significantly larger than oxides and sulfides.

Thus, the rating of non-metallic inclusions proves that all the inclusions are of a complex composition, predominantly of globular shape and randomly located. All these factors are beneficial for the technological properties of steel.

Somehow, in compliance with modern concepts on the role of sulfur in the formation of steel properties [5–10], it was demonstrated that the adverse affect of sulfur inclusions is due not so much to their numbers, but to the features of their formation and location, as well as the im-

part of melt oxidation on these features. In other words, the formation of sulfides of the preferred globular shape depends on the share of oxides, sulfides and oxysulfides which are interrelated among themselves.

Consequently, the paper investigates a possible interrelation between oxide, sulfide and oxysulfide contamination index throughout the ingot mass (fig. 1) as well as the distribution of impurities in each structural zone of the ingot (fig. 2).

An increased number of sulfides and oxysulfides is found in the upper part of the ingot and below its hot top (see fig. 1, *f*) in the columnar crystal zone, while oxide contamination is absent. When approaching the ingot's 1/2R, oxide contamination increases while sulfide and oxysulfide contamination decreases. The ingot axial sponginess zone is characterized by a decrease in oxide contamination and an increase in sulfide contamination.

At the ingot height of 2000 mm (see fig. 1, *e*) sulfide inclusions prevail throughout the ingot cross-section area, the sulfide amount growing from the periphery to the ingot axis by 2.5 times. At a distance of 1/2R, oxysulfide contamination decreases with an increase in the amount of oxides. In the axial sponginess zone the number of oxides, sulfides and oxysulfides grows by 2.5 times.

At the ingot height of 1650 mm (see fig. 1, *d*) in the zone of columnar and large randomly oriented crystals

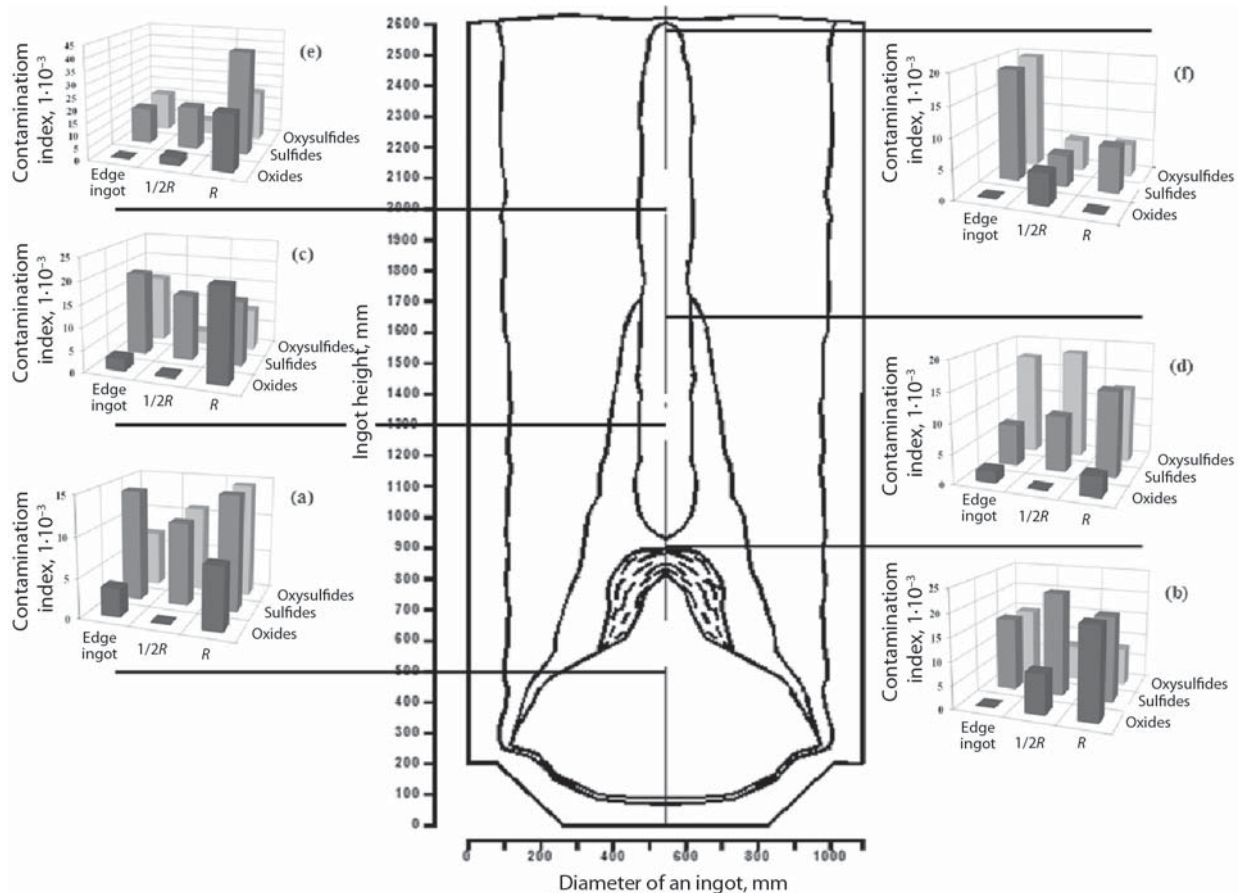
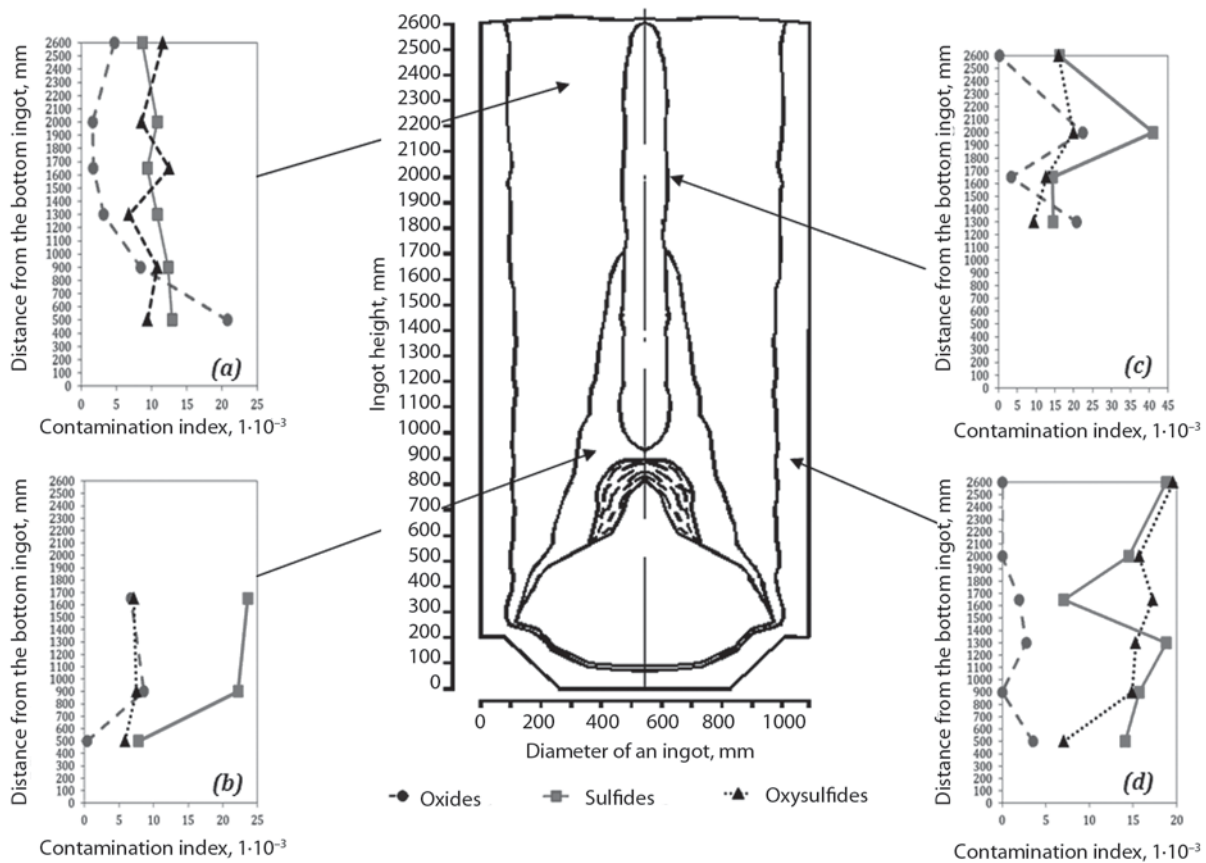


Fig. 2. Distribution of non-metallic inclusion contamination index at various levels of a 24.2 ton ingot of 38XH3MΦA steel: *a* — ingot height is 2600 mm; *b* — ingot height is 2000 mm; *c* — ingot height is 1650 mm; *d* — ingot height is 1300 mm; *e* — ingot height is 900 mm; *f* — ingot height is 500 mm





**Fig. 3. Distribution of the average values of non-metallic inclusion contamination index in the ingot structural zones throughout the ingot height:**

*a, b* — zone of large and fine randomly oriented crystals; *c* — axial sponginess zone; *d* — columnar crystal zone

the oxysulfide contamination increases by 2.5 times. The increase is accompanied by a decrease in oxide contamination and an increase in oxysulfide numbers. When approaching the axial sponginess zone, oxide and sulfide contamination grows, and the amount of oxysulfides falls.

Sulfide inclusions prevail at the middle level of the ingot (fig. 1, c) in the zone of columnar and large randomly oriented crystals. In the axial sponginess zone oxide contamination increases also by 20 times which leads to a twofold increase in the number of oxysulfides.

At the level of 900 mm from the ingot bottom (fig. 1, b) the number of oxides is increasing, their amount growing by 20 times from the ingot periphery to the axis. At a distance of  $\frac{1}{2}R$  oxysulfide contamination drops twofold, while the amount of sulfides rises by the same amount. Sulfide contamination decreases in the axial zone while oxide contamination increases; it results in an insignificant growth of steel contamination with oxysulfide inclusions.

At the ingot lower level (see fig. 1, a) oxide contamination equals zero at a distance of  $\frac{1}{2}R$ , while oxysulfide contamination increases twofold and sulfide contamination decreases by the same amount. Closer to the ingot axis oxide contamination increases eightfold, accompanied with an increase in sulfide and oxysulfide contamination.

The curves demonstrate that there exists a certain correlation between sulfide and oxysulfide contamination index and the ingot height. In the upper part of the ingot,

below its hot top, the distribution of the inclusions and their numbers almost fully coincide due to an extended heat exposure. In the middle and bottom parts of the ingot in the zone of columnar and large oriented crystals there is a pronounced inverse relation between the distribution of sulfides and oxysulfides.

The data obtained support the findings in [11, 12] regarding the features of the formation of sulfides and oxysulfides in order to achieve a minimal “pure” sulfide phase at grain boundaries.

The curves with the average values of the non-metallic contamination index in ingot structural zones throughout the ingot height are plotted in fig. 2. As is clear from the diagrams, oxide contamination tends to vanish in the columnar crystal zone, while sulfide and oxysulfide contamination increases with the ingot height.

The large randomly oriented crystal zone is characterized by heavy oxide contamination at the ingot’s bottom level. This contamination exceeds by 12 times that at the middle level and by 4 times that at the upper level. It can be explained by the fact that oxides, being heat resistant exogenous particles, serve as crystal seeds to form heterogeneous crystal nuclei which later precipitate to the ingot bottom. The contamination with sulfide and oxysulfide inclusions remains practically unchanged throughout the ingot height.

The zone of fine randomly oriented crystals is characterized by an increase in all types of inclusions throughout

the ingot height from bottom to top. Somehow, sulfide contamination is the highest and it increases fourfold. Low-melting non-metallic inclusions are pushed out to the upper part of the ingot while solid crystals (oxides), which are formed at higher temperatures, precipitate at the ingot bottom.

A growth in sulfide contamination closer to the ingot axial zone (see **fig. 1, a–d** and **fig. 2**) can be explained by the slowing down of solidification rate: in this case, favorable conditions are formed for the segregation of elements from solid to liquid phase followed by supplementation with low-melting inclusions.

The distribution of oxides and sulfides in the ingot reveals an inverse relation between the amount of inclusions in the middle and bottom parts of the ingot. This fact indicates that oxysulfides prevail when forming sulfides, which are typically located at grain boundaries and decrease steel ductility [2, 11]. This fact is particularly important for vacuum cast steel, since oxygen shortage leads to a decrease in the amount of oxysulfides and entails sulfide escape in an undesired form.

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